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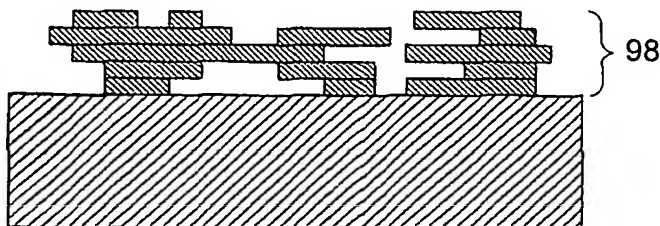
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(54) Title: METHODS AND APPARATUS FOR MONITORING DEPOSITION QUALITY DURING CONFORMABLE CON-
TACT MASK PLASTING OPERATIONS



(57) Abstract: Electrochemical fabrication (*e.g.* EFAB) processes and apparatus are disclosed that provide monitoring of at least one electrical parameter (*e.g.* voltage) during selective deposition where the monitored parameter is used to help determine the quality of the deposition that was made. If the monitored parameter indicates that a problem occurred with the deposition, various remedial operations may be undertaken to allow successful formation of the structure to be completed.

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Related Applications

This application claims benefit of U.S. Provisional Patent Application No. 60/379,132, filed on May 7, 2002 which is hereby incorporated herein by reference as if set forth in full.

5 Government Support

Certain embodiments of certain aspects of this invention were made with Government support under Grant Number DABT63-97-C-0051 awarded by DARPA. The Government may have certain rights.

Field of the Invention

10 Embodiments of this invention relate to the field of electrochemical fabrication and to the associated electrochemical deposition of materials, some of which involve the use of masks for selective patterning operations (e.g. selective electrochemical deposition operations) according to desired cross-sectional configurations and in some embodiments to the build up of multi-layer three-dimensional structures from a
15 plurality of adhered layers of deposited material.

Background

A technique for forming three-dimensional structures (e.g. parts, components, devices, and the like) from a plurality of adhered layers was invented by Adam L. Cohen and is known as Electrochemical Fabrication. It is being commercially
20 pursued by MEMGen[®] Corporation of Burbank, California under the name EFAB[™]. This technique was described in US Patent No. 6,027,630, issued on February 22, 2000. This electrochemical deposition technique allows the selective deposition of a material using a unique masking technique that involves the use of a mask that includes patterned conformable material on a support structure that is independent
25 of the substrate onto which plating will occur. When desiring to perform an electrodeposition using the mask, the conformable portion of the mask is brought into contact with a substrate while in the presence of a plating solution such that the contact of the conformable portion of the mask to the substrate inhibits deposition at selected locations. For convenience, these masks might be generically called
30 conformable contact masks; the masking technique may be generically called a

conformable contact mask plating process. More specifically, in the terminology of MEMGen[®] Corporation of Burbank, California such masks have come to be known as INSTANT MASKS[™] and the process known as INSTANT MASKING[™] or INSTANT MASK[™] plating. Selective depositions using conformable contact mask plating may be used to form single layers of material or may be used to form multi-layer structures. The teachings of the '630 patent are hereby incorporated herein by reference as if set forth in full herein. Since the filing of the patent application that led to the above noted patent, various papers about conformable contact mask plating (i.e. INSTANT MASKING) and electrochemical fabrication have been published:

1. A. Cohen, G. Zhang, F. Tseng, F. Mansfeld, U. Frodis and P. Will, "EFAB: Batch production of functional, fully-dense metal parts with micro-scale features", Proc. 9th Solid Freeform Fabrication, The University of Texas at Austin, p161, Aug. 1998.
2. A. Cohen, G. Zhang, F. Tseng, F. Mansfeld, U. Frodis and P. Will, "EFAB: Rapid, Low-Cost Desktop Micromachining of High Aspect Ratio True 3-D MEMS", Proc. 12th IEEE Micro Electro Mechanical Systems Workshop, IEEE, p244, Jan 1999.
3. A. Cohen, "3-D Micromachining by Electrochemical Fabrication", Micromachine Devices, March 1999.
4. G. Zhang, A. Cohen, U. Frodis, F. Tseng, F. Mansfeld, and P. Will, "EFAB: Rapid Desktop Manufacturing of True 3-D Microstructures", Proc. 2nd International Conference on Integrated MicroNanotechnology for Space Applications, The Aerospace Co., Apr. 1999.
5. F. Tseng, U. Frodis, G. Zhang, A. Cohen, F. Mansfeld, and P. Will, "EFAB: High Aspect Ratio, Arbitrary 3-D Metal Microstructures using a Low-Cost Automated Batch Process", 3rd International Workshop on High Aspect Ratio MicroStructure Technology (HARMST'99), June 1999.
6. A. Cohen, U. Frodis, F. Tseng, G. Zhang, F. Mansfeld, and P. Will, "EFAB: Low-Cost, Automated Electrochemical Batch Fabrication of Arbitrary 3-D Microstructures", Micromachining and Microfabrication Process Technology, SPIE 1999 Symposium on Micromachining and Microfabrication, September 1999.

7. F. Tseng, G. Zhang, U. Frodis, A. Cohen, F. Mansfeld, and P. Will, "EFAB: High Aspect Ratio, Arbitrary 3-D Metal Microstructures using a Low-Cost Automated Batch Process", MEMS Symposium, ASME 1999 International Mechanical Engineering Congress and Exposition, November, 1999.
- 5 8. A. Cohen, "Electrochemical Fabrication (EFABTM)", Chapter 19 of The MEMS Handbook, edited by Mohamed Gad-El-Hak, CRC Press, 2002.
9. "Microfabrication - Rapid Prototyping's Killer Application", pages 1 - 5 of the Rapid Prototyping Report, CAD/CAM Publishing, Inc., June 1999.

10 The disclosures of these nine publications are hereby incorporated herein by reference as if set forth in full herein.

The electrochemical deposition process may be carried out in a number of different ways as set forth in the above patent and publications. In one form, this process involves the execution of three separate operations during the formation of each layer of the structure that is to be formed:

- 15 1. Selectively depositing at least one material by electrodeposition upon one or more desired regions of a substrate.
2. Then, blanket depositing at least one additional material by electrodeposition so that the additional deposit covers both the regions that were previously selectively deposited onto, and the regions of the substrate that did not
20 receive any previously applied selective depositions.
3. Finally, planarizing the materials deposited during the first and second operations to produce a smoothed surface of a first layer of desired thickness having at least one region containing the at least one material and at least one region containing at least the one additional material.

25 After formation of the first layer, one or more additional layers may be formed adjacent to the immediately preceding layer and adhered to the smoothed surface of that preceding layer. These additional layers are formed by repeating the first through third operations one or more times wherein the formation of each subsequent layer treats the previously formed layers and the initial substrate as a
30 new and thickening substrate.

Once the formation of all layers has been completed, at least a portion of at least one of the materials deposited is generally removed by an etching process to expose or release the three-dimensional structure that was intended to be formed.

The preferred method of performing the selective electrodeposition involved in the first operation is by conformable contact mask plating. In this type of plating, one or more conformable contact (CC) masks are first formed. The CC masks include a support structure onto which a patterned conformable dielectric material is adhered or formed. The conformable material for each mask is shaped in accordance with a particular cross-section of material to be plated. At least one CC mask is needed for each unique cross-sectional pattern that is to be plated.

The support for a CC mask is typically a plate-like structure formed of a metal that is to be selectively electroplated and from which material to be plated will be dissolved. In this typical approach, the support will act as an anode in an electroplating process. In an alternative approach, the support may instead be a porous or otherwise perforated material through which deposition material will pass during an electroplating operation on its way from a distal anode to a deposition surface. In either approach, it is possible for CC masks to share a common support, i.e. the patterns of conformable dielectric material for plating multiple layers of material may be located in different areas of a single support structure. When a single support structure contains multiple plating patterns, the entire structure is referred to as the CC mask while the individual plating masks may be referred to as "submasks". In the present application such a distinction will be made only when relevant to a specific point being made.

In preparation for performing the selective deposition of the first operation, the conformable portion of the CC mask is placed in registration with and pressed against a selected portion of the substrate (or onto a previously formed layer or onto a previously deposited portion of a layer) on which deposition is to occur. The pressing together of the CC mask and substrate occur in such a way that all openings, in the conformable portions of the CC mask contain plating solution. The conformable material of the CC mask that contacts the substrate acts as a barrier to electrodeposition while the openings in the CC mask that are filled with electroplating solution act as pathways for transferring material from an anode (e.g. the CC mask support) to the non-contacted portions of the substrate (which act as a cathode during the plating operation) when an appropriate potential and/or current are supplied.

An example of a CC mask and CC mask plating are shown in Figures 1(a) - 1(c). Figure 1(a) shows a side view of a CC mask 8 consisting of a conformable or deformable (e.g. elastomeric) insulator 10 patterned on an anode 12. The anode has two functions. Figure 1(a) also depicts a substrate 6 separated from mask 8.

5 One is as a supporting material for the patterned insulator 10 to maintain its integrity and alignment since the pattern may be topologically complex (e.g., involving isolated "islands" of insulator material). The other function is as an anode for the electroplating operation. CC mask plating selectively deposits material 22 onto a substrate 6 by simply pressing the insulator against the substrate then

10 electrodepositing material through apertures 26a and 26b in the insulator as shown in Figure 1(b). After deposition, the CC mask is separated, preferably non-destructively, from the substrate 6 as shown in Figure 1(c). The CC mask plating process is distinct from a "through-mask" plating process in that in a through-mask plating process the separation of the masking material from the substrate would

15 occur destructively. As with through-mask plating, CC mask plating deposits material selectively and simultaneously over the entire layer. The plated region may consist of one or more isolated plating regions where these isolated plating regions may belong to a single structure that is being formed or may belong to multiple structures that are being formed simultaneously. In CC mask plating as individual

20 masks are not intentionally destroyed in the removal process, they may be usable in multiple plating operations.

Another example of a CC mask and CC mask plating is shown in Figures 1(d) - 1(f). Figure 1(d) shows an anode 12' separated from a mask 8' that comprises a patterned conformable material 10' and a support structure 20. Figure 1(d) also

25 depicts substrate 6 separated from the mask 8'. Figure 1(e) illustrates the mask 8' being brought into contact with the substrate 6. Figure 1(f) illustrates the deposit 22' that results from conducting a current from the anode 12' to the substrate 6. Figure 1(g) illustrates the deposit 22' on substrate 6 after separation from mask 8'. In this example, an appropriate electrolyte is located between the substrate 6 and the

30 anode 12' and a current of ions coming from one or both of the solution and the anode are conducted through the opening in the mask to the substrate where material is deposited. This type of mask may be referred to as an anodeless INSTANT MASK™ (AIM) or as an anodeless conformable contact (ACC) mask.

Unlike through-mask plating, CC mask plating allows CC masks to be formed completely separate from the fabrication of the substrate on which plating is to occur (e.g. separate from a three-dimensional (3D) structure that is being formed). CC masks may be formed in a variety of ways, for example, a photolithographic process may be used. All masks can be generated simultaneously, prior to structure fabrication rather than during it. This separation makes possible a simple, low-cost, automated, self-contained, and internally-clean "desktop factory" that can be installed almost anywhere to fabricate 3D structures, leaving any required clean room processes, such as photolithography to be performed by service bureaus or the like.

An example of the electrochemical fabrication process discussed above is illustrated in Figures 2(a) - 2(f). These figures show that the process involves deposition of a first material 2 which is a sacrificial material and a second material 4 which is a structural material. The CC mask 8, in this example, includes a patterned conformable material (e.g. an elastomeric dielectric material) 10 and a support 12 which is made from deposition material 2. The conformal portion of the CC mask is pressed against substrate 6 with a plating solution 14 located within the openings 16 in the conformable material 10. An electric current, from power supply 18, is then passed through the plating solution 14 via (a) support 12 which doubles as an anode and (b) substrate 6 which doubles as a cathode. Figure 2(a), illustrates that the passing of current causes material 2 within the plating solution and material 2 from the anode 12 to be selectively transferred to and plated on the cathode 6. After electroplating the first deposition material 2 onto the substrate 6 using CC mask 8, the CC mask 8 is removed as shown in Figure 2(b). Figure 2(c) depicts the second deposition material 4 as having been blanket-deposited (i.e. non-selectively deposited) over the previously deposited first deposition material 2 as well as over the other portions of the substrate 6. The blanket deposition occurs by electroplating from an anode (not shown), composed of the second material, through an appropriate plating solution (not shown), and to the cathode/substrate 6. The entire two-material layer is then planarized to achieve precise thickness and flatness as shown in Figure 2(d). After repetition of this process for all layers, the multi-layer structure 20 formed of the second material 4 (i.e. structural material) is embedded in first material 2 (i.e. sacrificial material) as shown in Figure 2(e). The embedded

structure is etched to yield the desired device, i.e. structure 20, as shown in Figure 2(f).

Various components of an exemplary manual electrochemical fabrication system 32 are shown in Figures 3(a) - 3(c). The system 32 consists of several subsystems 34, 36, 38, and 40. The substrate holding subsystem 34 is depicted in the upper portions of each of Figures 3(a) to 3(c) and includes several components: (1) a carrier 48, (2) a metal substrate 6 onto which the layers are deposited, and (3) a linear slide 42 capable of moving the substrate 6 up and down relative to the carrier 48 in response to drive force from actuator 44. Subsystem 34 also includes an indicator 46 for measuring differences in vertical position of the substrate which may be used in setting or determining layer thicknesses and/or deposition thicknesses. The subsystem 34 further includes feet 68 for carrier 48 which can be precisely mounted on subsystem 36.

The CC mask subsystem 36 shown in the lower portion of Figure 3(a) includes several components: (1) a CC mask 8 that is actually made up of a number of CC masks (i.e. submasks) that share a common support/anode 12, (2) precision X-stage 54, (3) precision Y-stage 56, (4) frame 72 on which the feet 68 of subsystem 34 can mount, and (5) a tank 58 for containing the electrolyte 16. Subsystems 34 and 36 also include appropriate electrical connections (not shown) for connecting to an appropriate power source for driving the CC masking process.

The blanket deposition subsystem 38 is shown in the lower portion of Figure 3(b) and includes several components: (1) an anode 62, (2) an electrolyte tank 64 for holding plating solution 66, and (3) frame 74 on which the feet 68 of subsystem 34 may sit. Subsystem 38 also includes appropriate electrical connections (not shown) for connecting the anode to an appropriate power supply for driving the blanket deposition process.

The planarization subsystem 40 is shown in the lower portion of Figure 3(c) and includes a lapping plate 52 and associated motion and control systems (not shown) for planarizing the depositions.

Another method for forming microstructures from electroplated metals (i.e. using electrochemical fabrication techniques) is taught in US Patent No. 5,190,637 to Henry Guckel, entitled "Formation of Microstructures by Multiple Level Deep X-ray Lithography with Sacrificial Metal layers. This patent teaches the formation of metal

structure utilizing mask exposures. A first layer of a primary metal is electroplated onto an exposed plating base to fill a void in a photoresist, the photoresist is then removed and a secondary metal is electroplated over the first layer and over the plating base. The exposed surface of the secondary metal is then machined down to a height which exposes the first metal to produce a flat uniform surface extending across the both the primary and secondary metals. Formation of a second layer may then begin by applying a photoresist layer over the first layer and then repeating the process used to produce the first layer. The process is then repeated until the entire structure is formed and the secondary metal is removed by etching. The photoresist is formed over the plating base or previous layer by casting and the voids in the photoresist are formed by exposure of the photoresist through a patterned mask via X-rays or UV radiation.

A need remains for enhanced plating quality diagnostics for use with conformable contract mask plating and particularly for use when multiple layers will be deposited one after the other to form structures from a plurality of adhered layers. A further need remains for minimizing wasted time, effort, and material when diagnostics indicate that a failed or problematic deposition has occurred or has probably occurred.

Summary of the Invention

It is an object of certain aspects of the invention to provide a contact or adhered mask plating or electrochemical fabrication process or apparatus that provides enhanced understanding of the quality of attempted plating operations.

It is an object of certain aspects of the invention to provide a contact or adhered mask plating or electrochemical fabrication process or apparatus that provides for a reduction in wasted time when a faulty deposition has occurred or is believed likely to have occurred.

It is an object of certain aspects of the invention to provide a contact or adhered mask plating or electrochemical fabrication process or apparatus that provides for a reduction in the waste associated with previous operations when a faulty deposition has occurred or is believed likely to have occurred.

It is an object of certain aspects of the invention to provide a contact or adhered mask plating or electrochemical fabrication process or apparatus that

provides for a reduction in wasted material resulting from previous operations when a faulty deposition has occurred or is believed likely to have occurred.

Other objects and advantages of various aspects of the invention will be apparent to those of skill in the art upon review of the teachings herein. The various aspects of the invention, set forth explicitly herein or otherwise ascertained from the teachings herein, may address any one of the above objects alone or in combination, or alternatively may not address any of the objects set forth above but instead address some other object ascertained from the teachings herein. It is not intended that all of these objects be addressed by any single aspect of the invention even though that may be the case with regard to some aspects.

In a first aspect of the invention an electrochemical fabrication process for producing a three-dimensional structure from a plurality of adhered layers, includes: (A) selectively depositing at least a portion of a layer onto the substrate, wherein the substrate may comprise previously deposited material; (B) forming a plurality of layers such that successive layers are formed adjacent to and adhered to previously deposited layers, wherein said forming comprises repeating operation (A) a plurality of times; wherein at least a plurality of the selective depositing operations comprise: (1) locating a mask on, or in proximity to, a substrate; (2) in presence of a plating solution, conducting an electric current between an anode and the substrate through the at least one opening in the mask, such that a selected deposition material is deposited onto the substrate to form at least a portion of a layer; and (3) removing the mask from the substrate; and wherein during formation of a given layer, a voltage between the anode and cathode is monitored.

An electrochemical fabrication process for producing a three-dimensional structure from a plurality of adhered layers, the process comprising: (A) selectively depositing at least a portion of a layer onto the substrate, wherein the substrate may comprise previously deposited material; (B) forming a plurality of layers such that successive layers are formed adjacent to and adhered to previously deposited layers, wherein said forming comprises repeating operation (A) a plurality of times; wherein at least a plurality of the selective depositing operations comprise: (1) locating a mask on, or in proximity to, a substrate; (2) in presence of a plating solution, conducting an electric current between an anode and the substrate through the at least one opening in the mask, such that a selected deposition material is

deposited onto the substrate to form at least a portion of a layer; and (3) removing the mask from the substrate; and wherein during, or after, formation of a given layer, the layer is inspected or formation parameters are compared to anticipated parameter values such that if it is determined that the layer was not formed correctly, at least a portion of material deposited in association with the layer is removed and replacement material is deposited.

In a third aspect of the invention a conformable contact masking process for producing a structure, includes: (A) supplying at least one preformed mask that comprises a patterned dielectric material that includes at least one opening through which deposition can take place during the formation of at least a portion of a layer, and wherein the at least one mask comprises a support structure that supports the patterned dielectric material; and (B) selectively depositing at least a portion of a layer onto a substrate, comprising: (i) contacting the substrate and the dielectric material of the preformed mask; (ii) in presence of a plating solution, conducting an electric current through the at least one opening in the selected mask between an anode and the substrate such that a selected deposition material is deposited onto the substrate to form at least a portion of a layer; and (iii) separating the selected preformed mask from the substrate; wherein during formation of at a layer, a voltage between the anode and cathode is monitored.

In a fourth aspect of the invention a conformable contact masking process for producing a structure, includes: (A) supplying at least one preformed mask that comprises a patterned dielectric material that includes at least one opening through which deposition can take place during the formation of at least a portion of a layer, and wherein the at least one mask comprises a support structure that supports the patterned dielectric material; and (B) selectively depositing at least a portion of a layer onto a substrate, comprising: (i) contacting the substrate and the dielectric material of the preformed mask; (ii) in presence of a plating solution, conducting an electric current through the at least one opening in the selected mask between an anode and the substrate such that a selected deposition material is deposited onto the substrate to form at least a portion of a layer; and (iii) separating the selected preformed mask from the substrate; wherein during, or after, formation of a given layer, the layer is inspected, or formation parameters are compared to anticipated parameter values, such that if it is determined that the layer was not formed

correctly, at least a portion of material deposited in association with the layer is removed and replacement material is deposited.

In a fifth aspect of the invention an electrochemical fabrication apparatus for producing a three-dimensional structure from a plurality of adhered layers, includes:

- 5 (A) means for selectively depositing at least a portion of a layer onto a substrate, wherein the substrate may comprise previously deposited material; and (B) means for forming a plurality of layers such that each successive layer is formed adjacent to and adhered to a previously deposited layer, wherein said forming comprises repeating operation (A) a plurality of times; wherein the means for selectively
10 depositing comprises: (1) means for locating, or placing in proximity, a patterned mask and the substrate; (2) means for conducting, in presence of a plating solution, an electric current through the at least one opening in the selected mask between an anode and the substrate such that the selected deposition material is deposited onto the substrate to form at least a portion of a layer; and (3) means for removing the
15 selected preformed mask from the substrate; and (C) means for monitoring a voltage between the anode and cathode during selective deposition.

In a sixth aspect of the invention an electrochemical fabrication apparatus for producing a three-dimensional structure from a plurality of adhered layers, includes:

- (A) means for selectively depositing at least a portion of a layer onto a substrate,
20 wherein the substrate may comprise previously deposited material; and (B) means for forming a plurality of layers such that each successive layer is formed adjacent to and adhered to a previously deposited layer, wherein said forming comprises repeating operation (A) a plurality of times; wherein the means for selectively depositing comprises: (1) means for locating, or placing in proximity, a patterned
25 mask and the substrate; (2) means for conducting, in presence of a plating solution, an electric current through the at least one opening in the selected mask between an anode and the substrate such that the selected deposition material is deposited onto the substrate to form at least a portion of a layer; and (3) means for removing the selected preformed mask from the substrate; and (C) means for inspecting
30 formation parameters or comparing formation parameters to anticipated parameter values; and (D) means for removing at least a portion of material deposited in association with the layer and for depositing replacement material if it is determined that a layer was not formed correctly.

Further aspects of the invention will be understood by those of skill in the art upon reviewing the teachings herein. Other aspects of the invention may involve combinations of the above noted aspects of the invention and/or addition of various features of one or more embodiments. Other aspects of the invention may involve apparatus that can be used in implementing one or more of the above method aspects of the invention. These other aspects of the invention may provide various combinations of the aspects presented above as well as provide other configurations, structures, functional relationships, and processes that have not been specifically set forth above.

10 **Brief Description of the Drawings:**

Figures 1(a) - 1(c) schematically depict side views of various stages of a CC mask plating process, while Figures 1(d) - (g) schematically depict a side views of various stages of a CC mask plating process using a different type of CC mask.

Figures 2(a) - 2(f) schematically depict side views of various stages of an electrochemical fabrication process as applied to the formation of a particular structure where a sacrificial material is selectively deposited while a structural material is blanket deposited.

Figures 3(a) - 3(c) schematically depict side views of various example subassemblies that may be used in manually implementing the electrochemical fabrication method depicted in Figures 2(a) - 2(f).

Figures 4(a) - 4(i) schematically depict the formation of a first layer of a structure using adhered mask plating where the blanket deposition of a second material overlays both the openings between deposition locations of a first material and the first material itself.

Figure 5 shows combined anodic and cathodic polarization curves for a particular copper bath operated at 20 °C and at 50 °C.

Figures 6(a) - 6(c) depict plots of cell voltage versus plating time for a first plating bath when three different deposition results have occurred.

Figures 7(a) and 7(b) depict plots of cell voltage versus plating time for a first plating bath when two different deposition results have occurred.

Figure 8 depicts a copper deposits where spiking has occurred.

Detailed Description

Figures 1(a) - 1(g), 2(a) - 2(f), and 3(a) - 3(c) illustrate various features of one form of electrochemical fabrication that are known. Other electrochemical fabrication techniques are set forth in the '630 patent referenced above, in the various
5 previously incorporated publications, in various other patents and patent applications incorporated herein by reference, still others may be derived from combinations of various approaches described in these publications, patents, and applications, or are otherwise known or ascertainable by those of skill in the art from the teachings set forth herein. All of these techniques may be combined with those of the various
10 embodiments of various aspects of the invention to yield enhanced embodiments. Still other embodiments may be derived from combinations of the various embodiments explicitly set forth herein.

Figures 4(a)-4(i) illustrate various stages in the formation of a single layer of a multi-layer fabrication process where a second metal is deposited on a first metal as
15 well as in openings in the first metal where its deposition forms part of the layer. In Figure 4(a), a side view of a substrate 82 is shown, onto which patternable photoresist 84 is cast as shown in Figure 4(b). In Figure 4(c), a pattern of resist is shown that results from the curing, exposing, and developing of the resist. The patterning of the photoresist 84 results in openings or apertures 92(a) - 92(c)
20 extending from a surface 86 of the photoresist through the thickness of the photoresist to surface 88 of the substrate 82. In Figure 4(d), a metal 94 (e.g. nickel) is shown as having been electroplated into the openings 92(a) - 92(c). In Figure 4(e), the photoresist has been removed (i.e. chemically stripped) from the substrate to expose regions of the substrate 82 which are not covered with the first metal 94.
25 In Figure 4(f), a second metal 96 (e.g., silver) is shown as having been blanket electroplated over the entire exposed portions of the substrate 82 (which is conductive) and over the first metal 94 (which is also conductive). Figure 4(g) depicts the completed first layer of the structure which has resulted from the planarization of the first and second metals down to a height that exposes the first
30 metal and sets a thickness for the first layer. In Figure 4(h) the result of repeating the process steps shown in Figures 4(b) - 4 (g) several times to form a multi-layer structure are shown where each layer consists of two materials. For most

applications, one of these materials is removed as shown in Figure 4(i) to yield a desired 3-D structure 98 (e.g. component or device).

Though the embodiments discussed herein are primarily focused on conformable contact masks and masking operations, the various embodiments, alternatives, and techniques disclosed herein may have application to proximity masks and masking operations (i.e. operations that use masks that at least partially selectively shield a substrate by their proximity to the substrate even if contact is not made), non-conformable masks and masking operations (i.e. masks and operations based on masks whose contact surfaces are not significantly conformable), and adhered masks and masking operations (masks and operations that use masks that are adhered to a substrate onto which selective deposition or etching is to occur as opposed to only being contacted to it).

A basic standard plating configuration (i.e. non-CC mask plating configuration) includes an anode and a cathode which are immersed in a plating bath. The distance between the anode and cathode is at least 1 mm. A power source provides a pre-set current passing through the plating cell so that the anode metal usually dissolves into the plating bath and the metal ions in the plating bath are reduced at the cathode to become a metallic deposit. Depending on various parameters, including the composition of the plating bath, the plating bath is usually operated at a constant temperature some wherein the range of between 20 - 60°C. The plating bath is agitated mechanically or by compressed air to ensure that fresh plating solution is delivered to the cathode and that the products of the electrochemical reactions are removed from the electrodes into the bulk solution.

Through-mask plating is a selective plating process since the substrate (cathode) is patterned by a thin non-conductive material (e.g. a patterned photoresist). Otherwise, its plating configuration is the same as that of standard plating process as outlined above. As such, through-mask plating, for the purposes herein, may be considered a selective form of standard plating.

CC mask plating is different from normal and through-mask plating in several aspects. In one form of CC mask plating, the plating bath is trapped in a closed volume defined by the substrate, the side walls of the conformable material, and the anode. Examples of such closed volumes 26a and 26b are depicted in Figure 1(b). Another form of CC mask plating may involve the use of a porous support and a

distal anode. In this alternative form of CC mask plating, the barrier presented by the support portion of the CC mask, though allowing at least some ion exchange, may present a sufficient hindrance to the exchange of some components of the plating solution that the solution in the deposition region may still be considered to be substantially isolated from the bulk solution. This trapping results in little or no mass exchange between the volume of solution in the plating region and the bulk solution and as such no or little fresh solution with proper additives can be supplied into the microspace and no or little reaction products can be removed.

A preferred form of CC mask plating involves closed volumes where at least one of the dimensions of at least one of the plating volumes is on the order of tens of microns (e.g. 20 to 100 μm) or less. As such, this form of CC mask plating may be considered to be a microbath plating process (i.e. micro-CC mask plating).

In micro-CC mask plating, the preferred separation between the anode and cathode is presently between about 20 μm and about 100 μm , and more preferably between about 40 and 80 μm . As such, regardless of the size of the area being deposited, these preferred embodiments may be considered to be micro-CC mask plating processes. Of course thinner separation distances (e.g. 10 μm or less) and thicker separation distances (300 μm or more) are possible. Due to this close spacing between anode and cathode, deposition processes at the cathode and dissolution processes at the anode, unlike standard plating, are highly interacting.

Agitating the plating bath, as is common with standard plating processes, though possible, is not necessarily desirable in electrochemical fabrication due potentially to the high interaction between anode and cathode processes and due to the believed enhanced risk of shorting when agitation is used. Shorting refers to a portion of the deposition height bridging the space between the cathode and the anode prior to the lapse of the desired deposition time, in which case the current is directed almost solely through deposited conductive material as opposed to flowing primarily through the plating bath as intended such that the continuing of deposition is inhibited.

Using a pyrophosphate bath at high temperature (i.e. above around 43 °C to 45 °C), though recommended in the standard plating processes, is not desirable in the current form of micro-CC mask plating due to the higher rate of attack at the

interface between the CC mask support and the conformable material and the associated shortening of CC mask life.

CC mask plating has its own characteristics and the conventional wisdom associated with standard plating processes may be more of a hindrance than a help in developing commercially viable CC mask plating processes and systems. The following Table provides a detailed comparison of various aspects of the two forms of standard plating (i.e. non-selective and through-mask plating) and micro-CC mask plating.

Characteristic	Standard Plating		Micro-CC mask plating
	Normal plating	Through-mask plating	
Patterned cathode	No	Yes	Yes
Separation between anode and cathode	Macroscale	Macroscale	Microscale, < ~ 80 μ m
Closed microbath plating	No	No	Yes
Bath agitation	Useful & Easy	Useful & Easy	Possible but problematic
Bath heating	Useful & Easy	Useful & Easy	Possible but problematic
Fresh bath supplied to electrodes	Yes	Yes	No
Products removed from electrodes	Yes	Yes	No
Cathode: anode area ratio	Variable	Variable	1:1
Plating time	Not limited	Not limited	Limited
Interaction between cathode and anode	Insignificant	Insignificant	Significant

10

It has been discovered that monitored cell voltage during the CC mask plating process can be correlated to various aspects of the quality of the depositions being made. This cell voltage information, alone or in combination with visual inspection, can be used to judge the acceptability of a given deposit that is being made or has been made. If the deposit is judged to be acceptable the process can be allowed to continue to the next deposition or other operation. If, on the other hand, the deposit is judged to be unacceptable, the process can be detoured to remove all or a portion of the unacceptable deposit and then redeposition can be attempted one or more

15

times until an acceptable deposition has been made after which the process can continue along its normal course.

The cell voltage is the potential between the anode and the cathode at a certain current density. It depends on the potential at the two electrodes, size and spacing of anode and cathode, the applied current, and the resistivity of the bath. The cell voltage can be expressed as

$$V_{\text{cell}} = V_{\text{anode}} + V_{\text{bath}} + V_{\text{cathode}}$$

where V_{anode} and V_{cathode} are the voltage drops at the anode and cathode due to polarization of the electrodes when passing a current through the bath, and V_{bath} is the voltage drop in the bath when a current passes through the bath between the anode and the cathode. V_{bath} can be calculated from

$$V_{\text{bath}} = IR$$

where I is the total current and R is the effective ohmic resistance of the bath. Since the gap between the anode and cathode is typically quite small (between about 25 - 100 μm), and the specific conductivity of several known plating baths are on the order of 10^{-1} , the voltage drop for a 20 mA/cm^2 current is on the order of tenths of millivolts to millivolts. As such, the voltage drop across a well behaved bath may be considered to be negligible compared to the voltage drops associated with the anode (V_{anode}) and the cathode (V_{cathode}). Using the polarization curve values for V_{anode} and V_{cathode} , the approximate value of the cell voltage can be estimated. Anodic and cathodic polarization curves measured in a plating bath indicate the potentials of the anode and the cathode at different current densities. Figure 5 shows a combined example of anodic and cathodic polarization curves measured in a copper plating bath (i.e. Cu-P bath from Technic of Cranston RI) at 20 and 50 °C without stirring. Both the anodic and cathodic electric potentials shown in Figure 5 are measured relative to a saturated calomel electrode and plotted against current density. From this diagram, the cell voltages at 20 mA/cm^2 can be determined to be between 1.9 and 1.3 V for the bath temperatures ranging from 20 to 50°C, respectively.

It has been determined that measurements of cell voltage during plating can provide information on several different plating conditions/results. In preferred embodiments the current supplied between the anode and the cathode is based on a known open area (i.e. plating area) of the conformable contact mask so that the total current supplied results in an average current density at the cathode that is equal to

A flash deposit is an unwanted additional deposit that extends beyond the intended masking area. In other words, the actual cathodic area is larger than expected and since the total current is constant, the actual current density at the cathode is less than expected. From the polarization curve in Figure 5, it can be seen that the cathodic potential will become more positive when the current density decreases, which in turn causes the overall cell voltage to decrease. Thus, if the monitored cell voltage is lower than expected, a flash deposit could be occurring. Fig. 7(a) shows a normal cell voltage, while the cell voltage in Fig. 7(b) is lower than the normal value.

For each deposition by conformable contact masking, the deposition process can be monitored wherein problems may be recognized during deposition or after the completion of a deposition. Based on an analysis of the resulting voltage curves in comparison to an anticipated curve or in comparison to a predefined acceptability or rejection criteria, a decision can be made as to whether or not the formation process can continue on course, whether the process should be aborted, or whether some form of remedial or corrective action should be taken. Problem detection may occur by operator review and analysis of one or more monitored electric signals (e.g. voltages), by automated system recognition, or by a combination of the two. Depending on the level of automation of the system and the believed severity of the problem, remedial action may be performed manually by an operator or under automated system control and it may involve a number of different operations:

(1) Visual or other secondary inspections may be performed to confirm that a problem occurred or to determine the severity of the problem so as to aid in making decisions on the most appropriate forms of additional remedial action to take, if any;

(2) If the offending deposition is still underway at the time of problem recognition,

- i. it may be aborted; or
- ii. it may be allowed to continue for a time;

(3) One or more additional depositions may be allowed to occur (e.g. to ensure full lateral support of the deposited structure)

a desired value. If plating operations are working properly, a predictable voltage should result.

It is anticipated that different plating baths, operating conditions, power supply control parameters and plating conditions may result in different characteristic voltage curves during plating. It is also anticipated that one of skill in the art can perform empirical tests to correlate acceptable plating or unacceptable plating to voltage values or curves (i.e. profiles over time) for different operating conditions. These correlated values or curves can be used to define acceptability criteria that can be used in determining the acceptability of subsequent plating operations.

Figures 6(a) and 7(a) show typical cell voltage curves for 4 minute plating times for two different copper pyrophosphate plating baths operated at room temperature. Figure 6(a) is based on the Cu-P plating bath while Figure 7(a) is based on a UNICHROME plating bath having the optimal formulation as recommended by Atotech. These curves were recorded on a strip chart recorder during actual plating. Under the conditions used, a normal plating process shows a smooth, stable curve of cell voltage vs. time. In addition, the cell voltage remained substantially constant (i.e. remained in a narrow range).

An example for a plating process failure is shown in Figure 6(c) where the large cell voltage change and instability of the cell voltage indicate that an improper plating operation is occurring and that the coating being applied will be lacking in one or more of the following: (1) the desired thickness, (2) desired uniformity, (3) desired bonding to the substrate, and/or (4) some other desired structural property.

Shorting can result from variations in deposit thickness. An SEM image of a copper layer produced by conformable contact mask plating with a deposition time of 30 minutes is shown in Figure 8. Many spikes 102 can be seen around the edges of the copper deposit 104. The big spikes 102 are higher than the rest of deposit. When one or more spikes extend in height enough to touch the anode, shorting occurs and the plating process can not proceed because the current is conducted through the lower resistance metal path instead of through the electrolyte. When shorting occurs, the cell voltage immediately drops to zero. Fig. 6(b) shows a plot of cell voltage versus time where shorting occurred in less than the anticipated plating time.

(4) A trimming process (e.g. planarization process by mechanical lapping or by CMP) may be implemented to remove all of, or just a portion of, the offending deposit.

5 (5) Complete or partial redeposition of the offending pattern may be undertaken

i. the same mask may be used in one or more subsequent attempts; or

ii an alternate mask may be used on one or more subsequent attempts; and

10 (6) If an optimal redeposition cannot be obtained, within a certain number of attempts, an automated system may be programmed to interrupt the formation process, pending operator intervention or to continue with the formation process while leaving behind an appropriate log of the issues encountered and remedial steps attempted.

15 Various embodiments of the present invention may be implemented using a single rejection criteria (e.g. shorting recognition) or using multiple rejection criteria. Each rejection criteria used may result in execution of the same remedial process or different rejection criteria may result in implementation of different remedial actions. In some embodiments remedial action may involve each of operations (1) to (6) as
20 noted above. In other embodiments only a subset of operations (1) to (6) may be used, for example (2)(ii) followed by (4) followed by (5)(b), and then by (6), if necessary. Each time operation (6) is encountered when a certain number of attempts have not yet been made, the remedial actions may be different. In some embodiments, if a problem associated with a given layer is believed to be the result
25 of a problem on a previous layer or if the remedial steps taken on the present layer may have negatively affected one or more previous layers, not only may one or more depositions associated with the present layer be trimmed away, but material may be trimmed from one or more previous layers. Redepositions of material for the present layer and for any previous layers of removed material may also be performed. In
30 some embodiments trimming operations may involve anodic etching as opposed to or in addition to other trimming processes. Various other problem recognition possibilities and remedial operation possibilities, and combinations will be apparent to those of skill in the art after review of the teachings herein.

Various other embodiments of the present invention exist. Some of these embodiments may be based on a combination of the teachings herein with various teachings incorporated herein by reference. Some embodiments may not use any blanket deposition process and/or they may not use a planarization process. Some
5 embodiments may involve the selective deposition of a plurality of different materials on a single layer or on different layers. Some embodiments may use blanket depositions processes that are not electrodeposition processes. Some embodiments may use selective deposition processes on some layers that are not conformable contact masking processes and are not even electrodeposition
10 processes. Some embodiments may use non-conformable masks, proximity masks, and/or adhered masks for selective patterning operations. Some embodiments may use nickel as a structural material while other embodiments may use different materials such as gold, silver, or any other electrodepositable materials that can be separated from the selected sacrificial material (e.g. copper and/or some other
15 sacrificial material). Some embodiments may use copper as the structural material with or without a sacrificial material. Some embodiments may remove a sacrificial material while other embodiments may not. In some embodiments the anode may be different from the conformable contact mask support and the support may be a porous structure or other perforated structure. Some embodiments may use multiple
20 conformable contact masks with different patterns so as to deposit different selective patterns of material on different layers and/or on different portions of a single layer. In some embodiments, the depth of deposition will be enhanced by pulling the conformable contact mask away from the substrate as deposition is occurring in a manner that allows the seal between the conformable portion of the CC mask and
25 the substrate to shift from the face of the conformal material to the inside edges of the conformable material. In some embodiments, monitoring of electrical parameters may not be performed or monitored parameters may not result in a conclusion to remove and re-deposit material, but instead such determination may be made by manual or automated visual inspection of a deposit.

30 In view of the teachings herein, many further embodiments, alternatives in design and uses of the instant invention will be apparent to those of skill in the art. As such, it is not intended that the invention be limited to the particular illustrative

embodiments, alternatives, and uses described above but instead that it be solely limited by the claims presented hereafter.

We claim:

1. An electrochemical fabrication process for producing a three-dimensional structure from a plurality of adhered layers, the process comprising:
 - (A) selectively depositing at least a portion of a layer onto the
5 substrate, wherein the substrate may comprise previously deposited material;
 - (B) forming a plurality of layers such that successive layers are formed adjacent to and adhered to previously deposited layers, wherein said forming comprises repeating operation (A) a plurality of times;
10 wherein at least a plurality of the selective depositing operations comprise:
 - (1) locating a mask on, or in proximity to, a substrate;
 - (2) in presence of a plating solution, conducting an electric current between an anode and the substrate through the at least one opening in the mask, such that a selected deposition material is deposited onto the
15 substrate to form at least a portion of a layer; and
 - (3) removing the mask from the substrate; and
wherein during formation of a given layer, a voltage between the anode and cathode is monitored.
- 20 2. The process of claim 1, wherein a plurality of layers comprise at least one structural material and at least one sacrificial material.
3. The process of claim 1 additionally comprising:
 - (C) supplying a plurality of preformed masks, wherein each mask
25 comprises a patterned dielectric material that includes at least one opening through which deposition can take place during the formation of at least a portion of a layer, and wherein each mask comprises a support structure that supports the patterned dielectric material; and
wherein the locating of a mask on, or in proximity to, a substrate
30 comprises contacting the substrate and the dielectric material of a selected preformed mask.

4. The process of claim 1 wherein the locating of a mask on, or in proximity to, a substrate comprises forming and adhering a patterned mask to the substrate.

5. The process of claim 1 wherein, based at least in part on the monitored voltage, a conclusion is reached that the deposition for a given layer is not acceptable, wherein the process additionally comprises:

(A) removing at least a portion of the material deposited in association with the given layer; and

(B) repeating the deposition for at least a portion of the given layer.

6. The process of claim 5 wherein the conclusion is also based on a visual inspection of the resulting deposit for a given layer.

7. The process of claim 5 wherein the measured voltage profile for at least one layer is indicative of flash.

8. The process of claim 5 wherein the comparison of the measured voltage profile to the anticipated voltage profile is capable of indicating the occurrence of flash.

9. The method of claim 5 wherein the measured voltage profile for at least one layer is indicative of shorting.

10. The method of claim 5 wherein the comparison of the measured voltage profile to the anticipated voltage profile is capable of indicating the occurrence of shorting.

11. An electrochemical fabrication process for producing a three-dimensional structure from a plurality of adhered layers, the process comprising:

(A) selectively depositing at least a portion of a layer onto the substrate, wherein the substrate may comprise previously deposited material;

(B) forming a plurality of layers such that successive layers are formed adjacent to and adhered to previously deposited layers, wherein said forming comprises repeating operation (A) a plurality of times;

wherein at least a plurality of the selective depositing operations

5 comprise:

(1) locating a mask on, or in proximity to, a substrate;

(2) in presence of a plating solution, conducting an electric current between an anode and the substrate through the at least one opening in the mask, such that a selected deposition material is deposited onto the
10 substrate to form at least a portion of a layer; and

(3) removing the mask from the substrate; and

wherein during, or after, formation of a given layer, the layer is inspected or formation parameters are compared to anticipated parameter values such that if it is determined that the layer was not formed correctly, at least a portion
15 of material deposited in association with the layer is removed and replacement material is deposited.

12. The process of claim 11, wherein a plurality of layers comprise at least one structural material and at least one sacrificial material.

20

13. The process of claim 11 additionally comprising:

(C) supplying a plurality of preformed masks, wherein each mask comprises a patterned dielectric material that includes at least one opening through which deposition can take place during the formation of at least a portion of a layer,
25 and wherein each mask comprises a support structure that supports the patterned dielectric material; and

wherein the locating of a mask on, or in proximity to, a substrate comprises contacting the substrate and the dielectric material of a selected preformed mask.

30

14. The process of claim 11 wherein the inspection comprises monitoring an electrical characteristic of a selective deposition operation.

15. The process of claim 14 wherein the electrical characteristic comprises a voltage between the anode and the cathode during conduction of the electric current.

5 16. The process of claim 14 wherein the monitoring occurs during formation of substantially all layers of the plurality.

17. The process of claims 15 wherein the monitored voltage for each layer comprises a measurement of a voltage profile over deposition time for each layer.

10 18. The process of claim 17 wherein at least two points of the measured voltage profile for a given layer are used in making a comparison to an anticipated voltage profile, and based at least in part on the result of the comparison, a conclusion is reached as to whether or not the deposition was acceptable.

15 19. The process of claim 11 wherein the formation of each of a number of layers comprise at least one blanket deposition as well as the selective deposition wherein for a given layer the selectively deposited material is different from a material deposited by blanket deposition.

20 20. The process of claim 11 wherein the plurality of selective depositions comprise the deposition of a plurality of different materials.

25 21. The process of claim 11 wherein at least a portion of one layer is formed by a non-electroplating deposition process.

30 22. The process of claim 11 wherein a plurality of depositions occur during the formation of each of a number of layers wherein at least one of the depositions on each of the number of layers deposits copper and at least one of the other depositions on the number of layers deposits nickel.

23. The process of claim 11 wherein the selective depositing for each of a number of layers comprises at least two selective depositions.

24. The process of claim 11 wherein a number of the plurality of layers are each formed by depositing at least one structural material using at least one deposition and by depositing at least one sacrificial material by using at least one other deposition.

25. The process of claim 21 wherein at least a portion of the at least one sacrificial material is removed after formation of a plurality of layers to reveal a three-dimensional structure comprised of at least one structural material.

10

26. A conformable contact masking process for producing a structure, wherein the process comprises:

(A) supplying at least one preformed mask that comprises a patterned dielectric material that includes at least one opening through which deposition can take place during the formation of at least a portion of a layer, and wherein the at least one mask comprises a support structure that supports the patterned dielectric material; and

15

(B) selectively depositing at least a portion of a layer onto a substrate, comprising:

20

i) contacting the substrate and the dielectric material of the preformed mask;

ii) in presence of a plating solution, conducting an electric current through the at least one opening in the selected mask between an anode and the substrate such that a selected deposition material is deposited onto the substrate to form at least a portion of a layer; and

25

iii) separating the selected preformed mask from the substrate; and

wherein during, or after, formation of a given layer, the layer is inspected, or formation parameters are compared to anticipated parameter values, such that if it is determined that the layer was not formed correctly, at least a portion of material deposited in association with the layer is removed and replacement material is deposited.

30

1/11

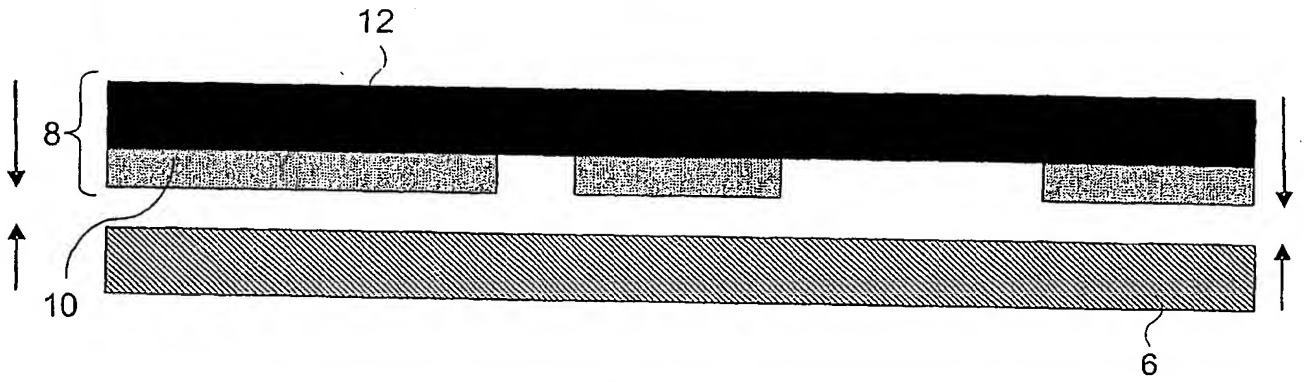


Figure 1(a)

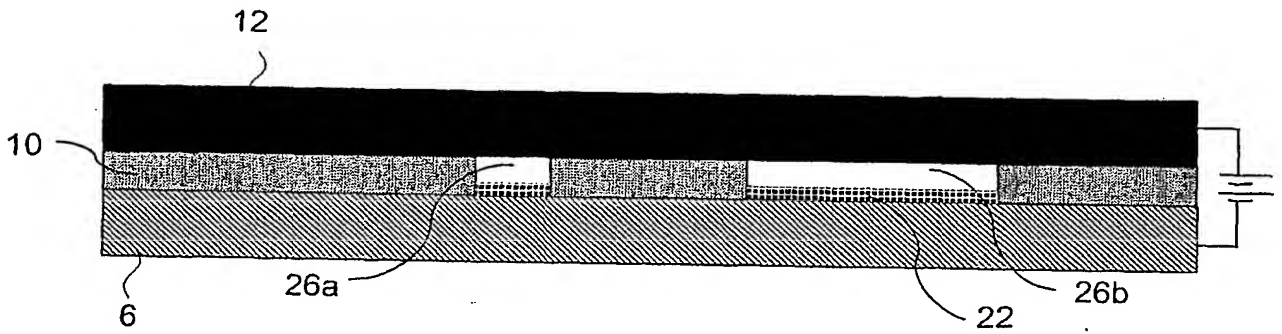


Figure 1(b)

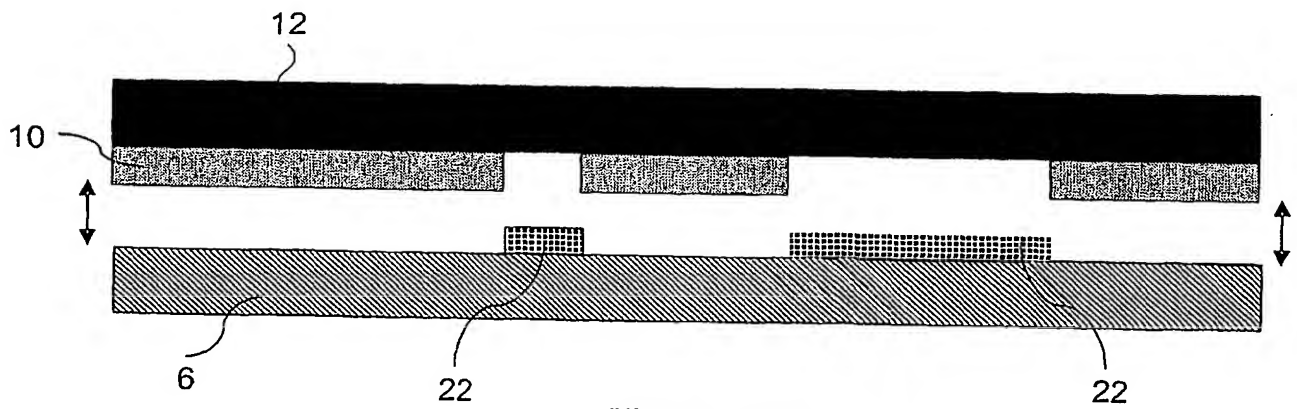


Figure 1(c)

2/11

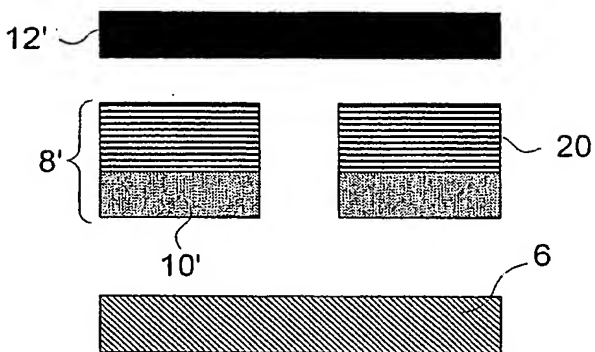


Figure 1(d)

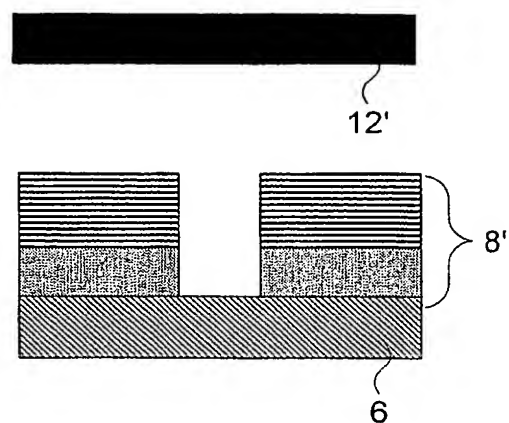


Figure 1(e)

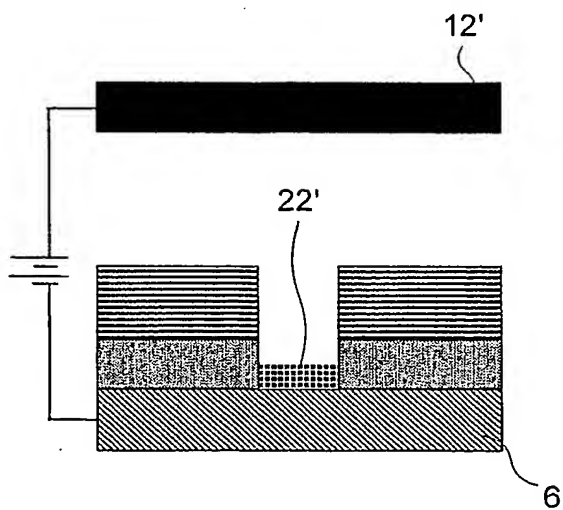


Figure 1(f)

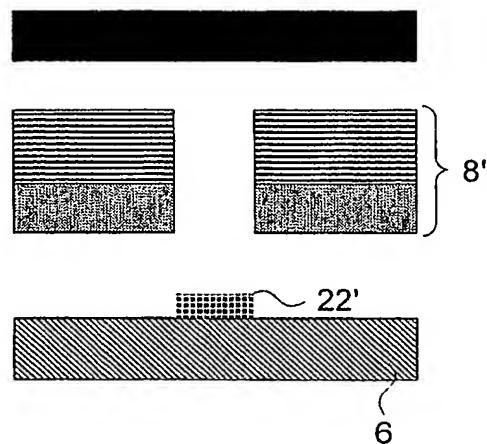


Figure 1(g)

3/11

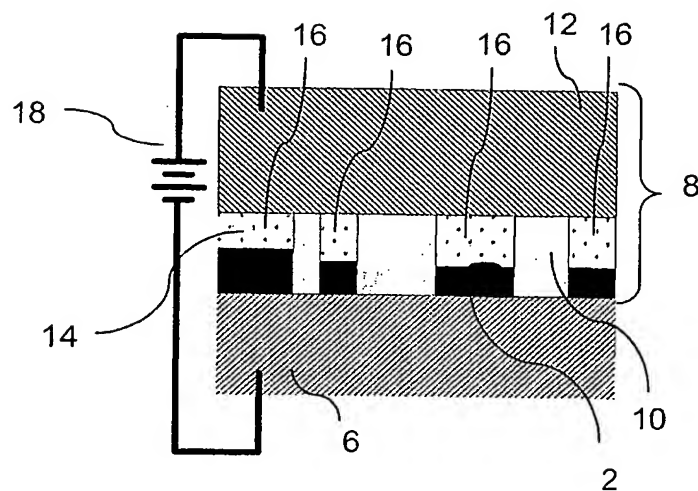


Figure 2(a)

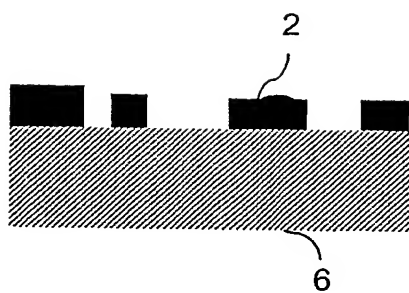


Figure 2(b)

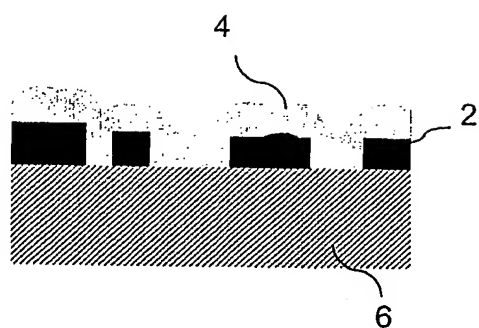


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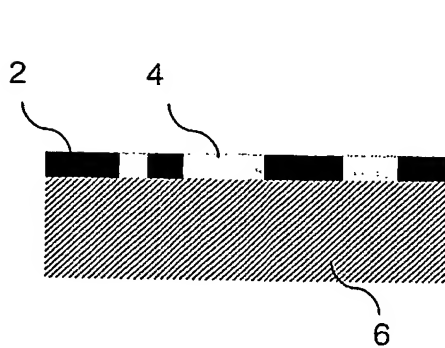


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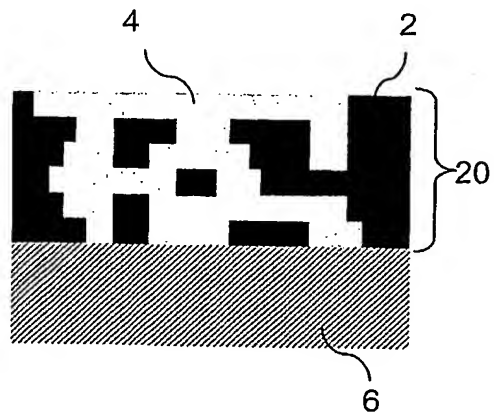


Figure 2(e)

4/11

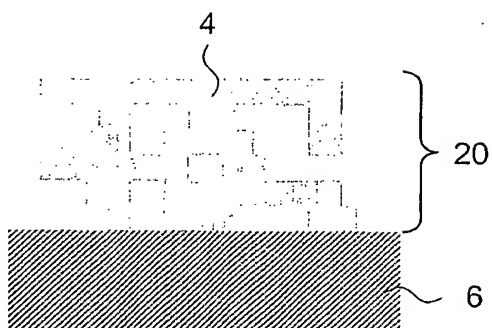


Figure 2(f)

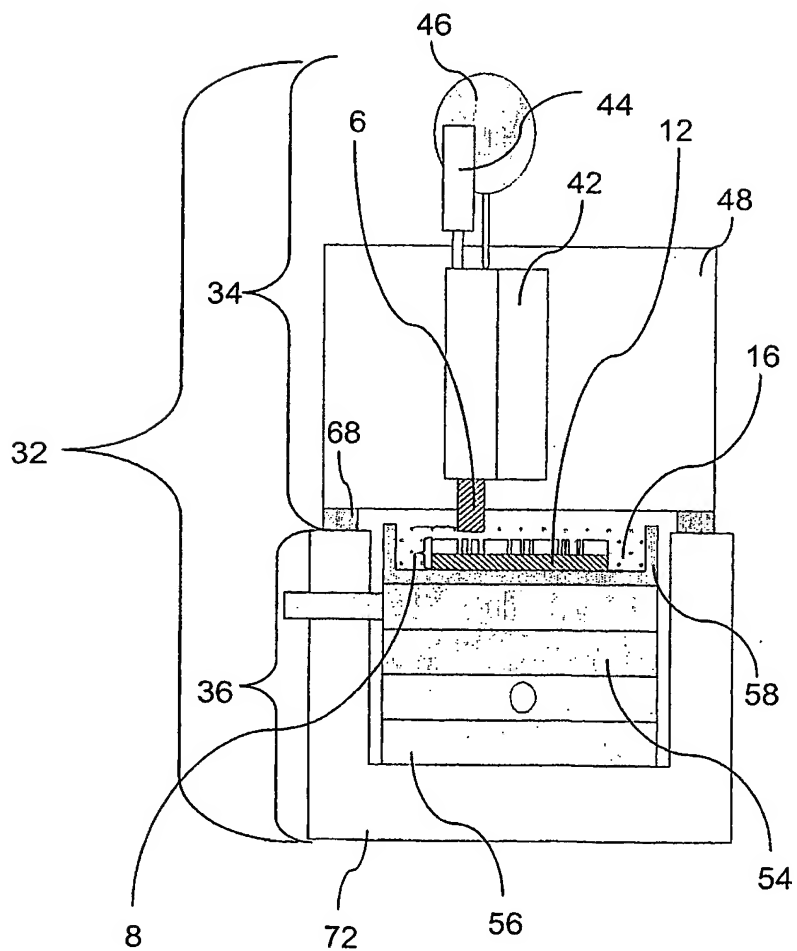


Figure 3(a)

5/11

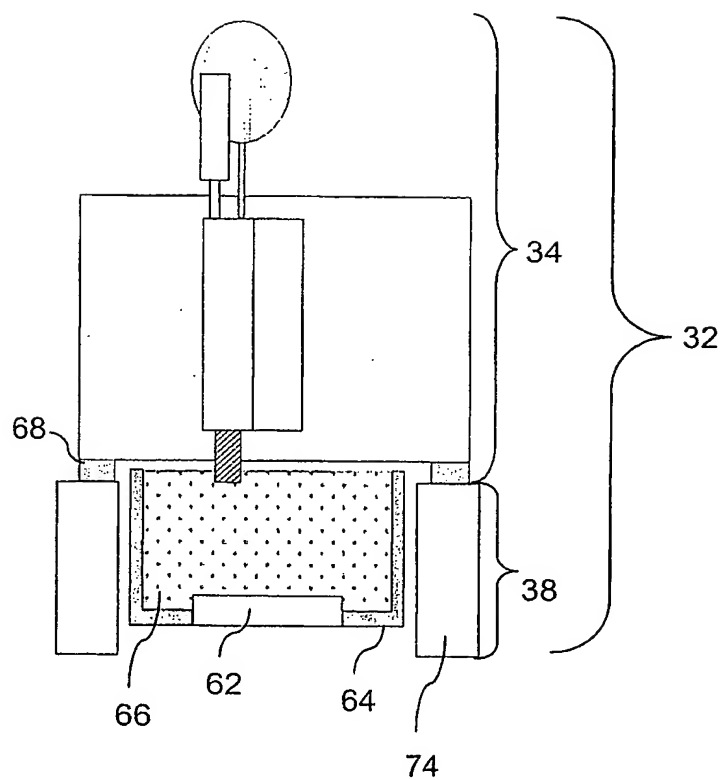


Figure 3(b)

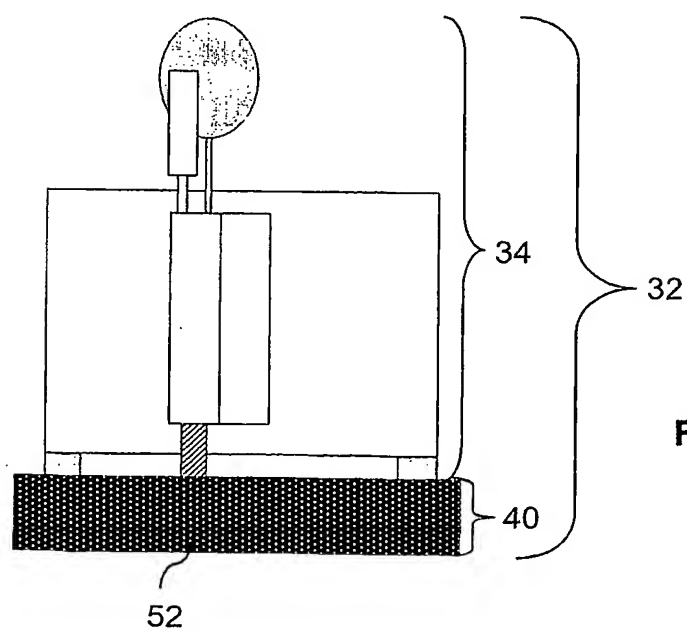


Figure 3(c)

6/11

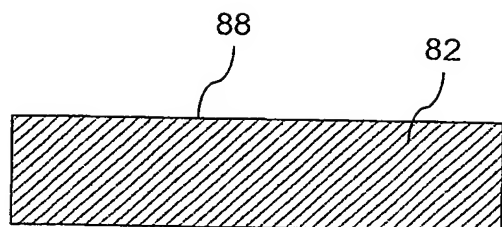


Figure 4(a)

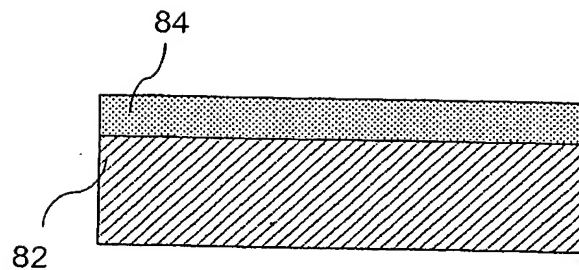


Figure 4(b)

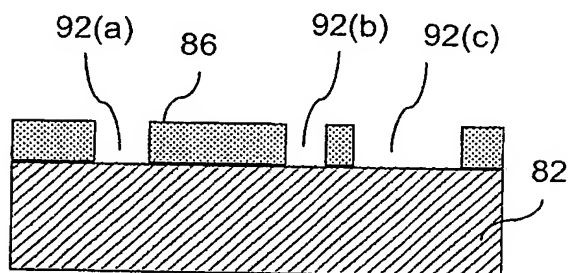


Figure 4(c)

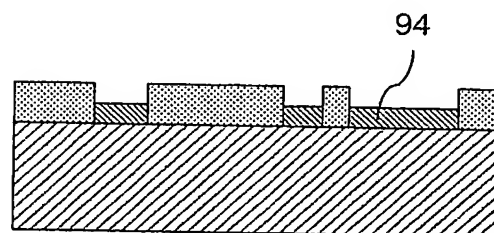


Figure 4(d)

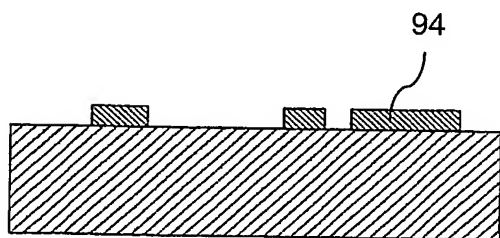


Figure 4(e)

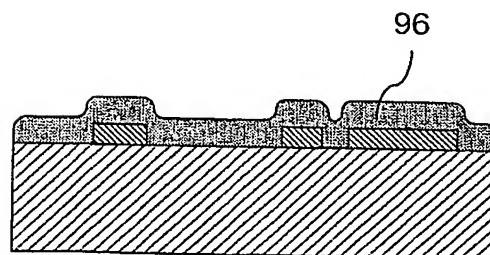


Figure 4(f)

7/11

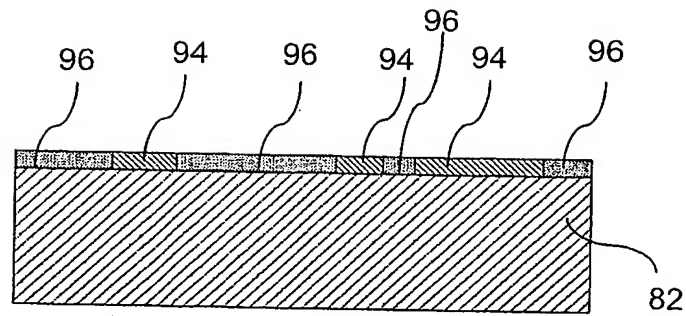


Figure 4(g)

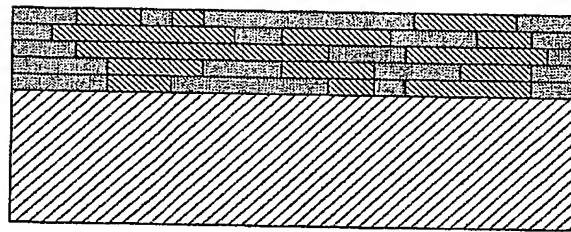


Figure 4(h)

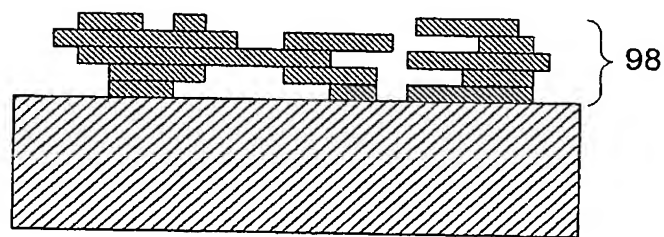


Figure 4(i)

8/11

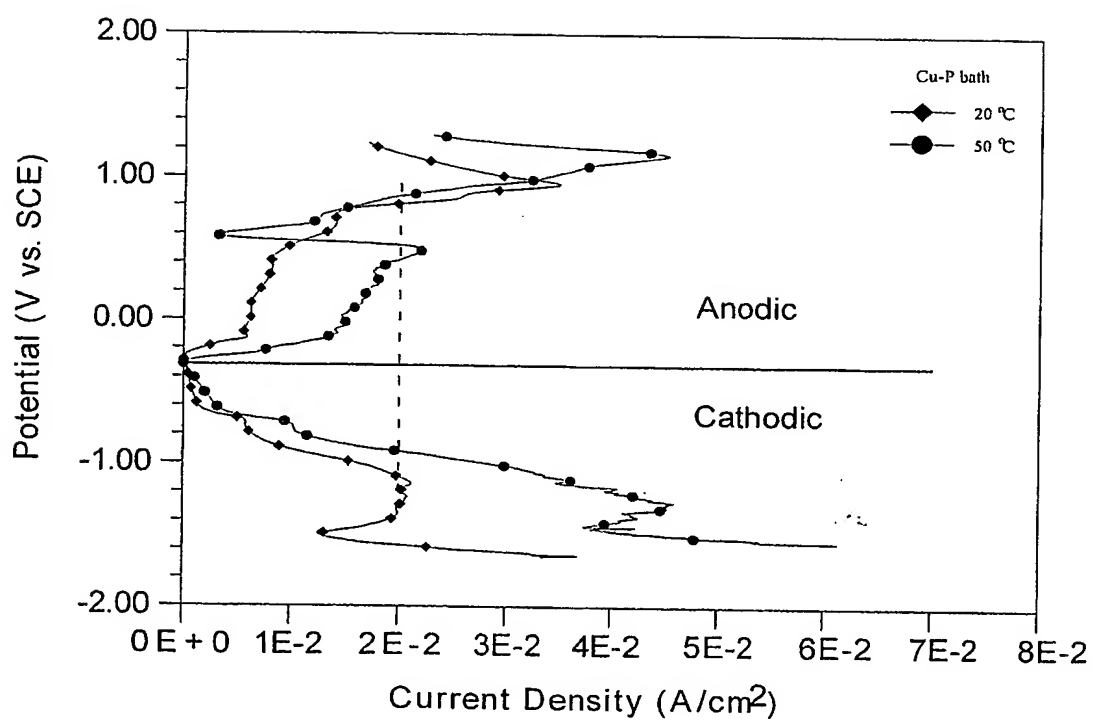


Figure 5

9/11

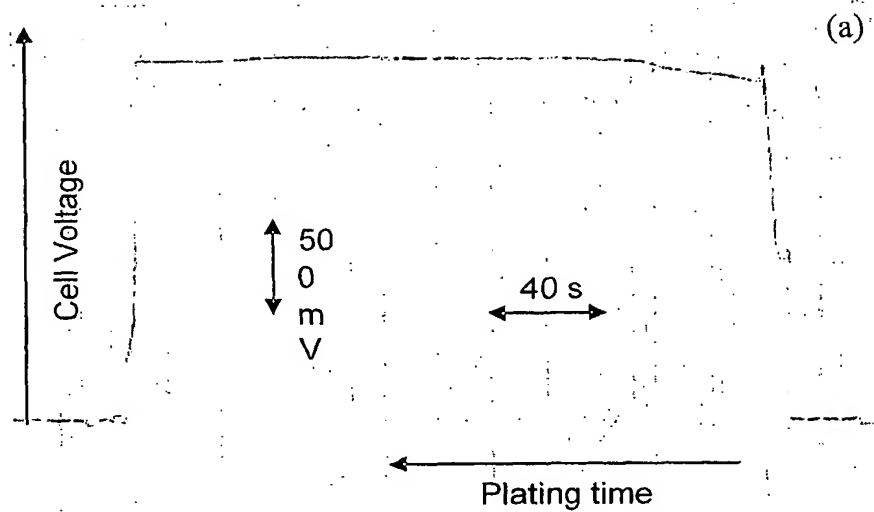


Figure 6(a)

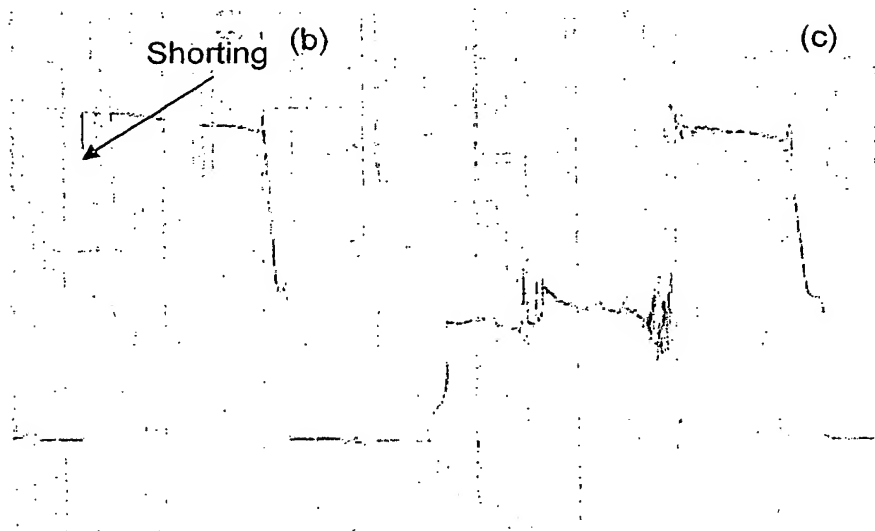


Figure 6(b)

Figure 6(c)

10/11

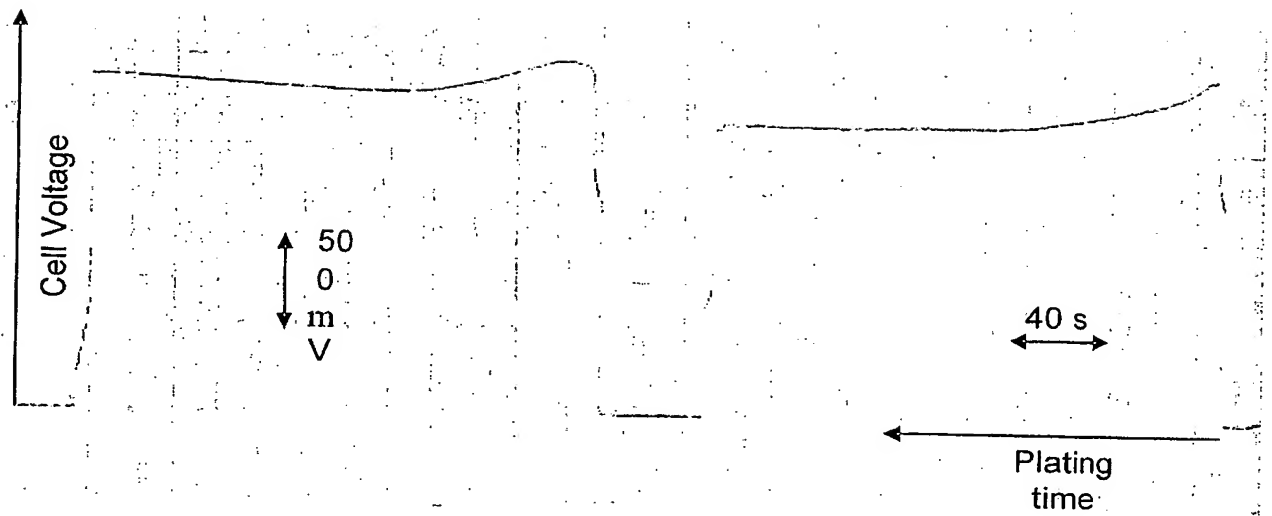


Figure 7(a)

Figure 7(b)

11/11

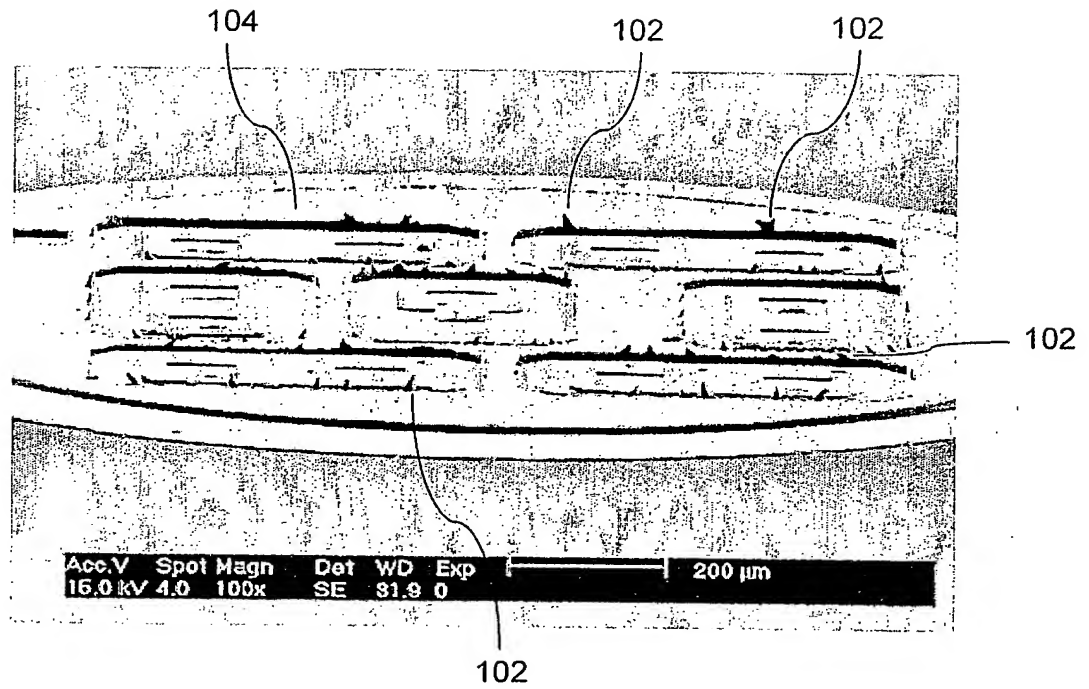


Figure 8

INTERNATIONAL SEARCH REPORT

International Application No.

PCT/US 03/14859

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 C25D21/12 C25D5/02 C25D5/12 C25D1/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 C25D H01L H05K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

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C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Date of the actual completion of the international search

8 September 2003

Date of mailing of the international search report

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INTERNATIONAL SEARCH REPORT

International Application No

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INTERNATIONAL SEARCH REPORT

Information on patent family members

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